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Physics Procedia 1 (2008) 185–191

**Physics
Procedia**

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Proceedings of the Seventh International Conference on Charged Particle Optics

Computer simulations of hexapole aberration correctors

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Received 9 July 2008; received in revised form 9 July 2008; accepted 9 July 2008

Abstract

The use of hexapole systems to correct the spherical aberration of the objective lenses of low-voltage scanning electron microscopes has been investigated. These systems are simpler than the more conventional quadrupole-octupole correctors, are easier to tune and are less sensitive to mechanical and electrical imperfections. We have considered two designs of telescopic corrector having the lens arrangements *RHRHR* and *HRRH*, where *R* and *H* represent round lenses and hexapole components respectively. Both designs give a significant correction of the objective lens spherical aberration but do not correct chromatic aberrations. The second design possesses some important advantages over the first: it is mechanically and electrically simpler and the tuning procedure is simpler. In the present investigation we have found the further advantages that the hexapole voltages are smaller for the second design, the aberration correction is better and the corrector is less sensitive to mechanical defects. On the other hand the chromatic aberration is larger for the second design.

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PACS: 02.70.Pt; 41.85.Gy; 41.85.Ne; 68.37.Hk

Keywords: Hexapole; Aberration; Corrector; SEM

1. Introduction

The resolving power of an electron microscope is limited by the third order spherical aberration and the first order chromatic aberration of the objective lens. One of the possible ways to improve the performance of the electron microscope is to employ a multipole system to correct these aberrations. Since the classical publication by Scherzer [1], who was the first to suggest that multipole correctors can be used, many efforts have been made to equip electron microscopes with quadrupole-octupole correctors which in principle allow correction of both chromatic and spherical aberrations. The first experiments were not successful mostly because the microscope performance was limited not by spherical and chromatic aberrations but by other imperfections, such as misalignments and instabilities.

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A significant improvement of the resolution by means of quadrupole-octupole corrector in a low-voltage scanning electron microscope was achieved only in 1995 [2]. The success resulted primarily from the progress made in stabilizing the electric and magnetic fields and from the use of computer-controlled alignment of correcting elements. Recently this type of aberration correction has come into the spotlight again [3, 4].

The correcting procedure in such a system is however very complicated and requires sophisticated skills. Also the requirements to the alignment accuracy and power supply stability are extremely high. On the other hand if the spherical aberration is dominant and therefore no chromatic aberration correction is required then much simpler multipole system based on hexapole elements can be used. In fact hexapole correctors have been investigated for both scanning and transmission electron microscopy [5-10]. In reference [10] a hexapole corrector was incorporated in a 200 kV TEM in order to demonstrate the compensation of the spherical aberration of the objective lens experimentally.

This paper presents a detailed study based on the computer simulation of hexapole correctors which are intended to be used in scanning electron microscopy. In particular, we are interested in correcting a low-voltage scanning electron microscope (LVSEM) which has a magnetic snorkel-type objective lens with $f = 2 \text{ mm}$, $C_s = 1.1 \text{ mm}$ and $C_c = 1.0 \text{ mm}$, and an analytical SEM (AnSEM) where the objective lens has $f = 17 \text{ mm}$, $C_s = 135 \text{ mm}$ and $C_c = 23 \text{ mm}$, both instruments using beam energies in the range 1 to 10 keV. Two types of the correctors are investigated: as proposed by Crewe and Kopf [5, 6] and as suggested by Rose [7, 8]. All the calculations are made with the CPO3D program [11] and restricted to electrostatic systems.

2. Principle of correction

A single hexapole consists of six electrodes arranged symmetrically around the optical axis with alternating voltages $\pm V$ applied to the electrodes. The near axis potential distribution is given by:

$$\phi(x, y, z) = P(z)(y^3 - 3x^2y) + \dots \quad (1)$$

if we assume that yz -plane is a plane of symmetry. The trajectory equations in the paraxial region of a hexapole can be written as

$$\begin{aligned} x'' &= -2k(z)xy + 0(4) + \dots \\ y'' &= k(z)(x^2 - y^2) + 0(4) + \dots \end{aligned} \quad (2)$$

Here the differentiation is with respect to z , and $k(z)$ is a parameter which denotes the strength of the hexapole normalized to the electron energy ($-e\Phi$):

$$k(z) = \frac{3}{2} \frac{P(z)}{\Phi} \quad (3)$$

It follows from Eqs. (2) that the primordial behaviour of hexapoles is quadratic, that they therefore have no linear focusing effect and that their primary aberrations are of third order. Thus hexapoles can only be used for the third order spherical aberration correction if the second order effects of the hexapoles are eliminated. Aberration analyses carried out by Crewe and colleagues [5, 6] and by Rose [7] have shown that in order for a hexapole system to make a good corrector it has to meet the following conditions:

- (1) It should contain at least two identical hexapoles of the same azimuthal orientation.
- (2) The corrector should be arranged and excited in such a way that an intermediate image is formed exactly in the middle between the two hexapoles.
- (3) The two hexapoles should be separated by round lens fields which image one hexapole on the other.

Meeting these conditions ensures that there are no second order aberrations in the beam which emerges from the corrector. The third order aberration in the emerging beam is cylindrically symmetric and has the opposite sign to the spherical aberration of the objective lens. The magnitude of the third order aberration of the hexapole system can be controlled by adjusting the hexapole voltages.

3. Geometry of the corrector

Two different designs which meet the above conditions are schematically shown in Fig. 1 and Fig. 2 respectively. The first scheme has been proposed by Crewe [6] and the second one is after Rose [8]. The corrector works as a telescopic system which transforms a parallel electron beam at the entrance into a parallel beam of the same diameter at the exit.

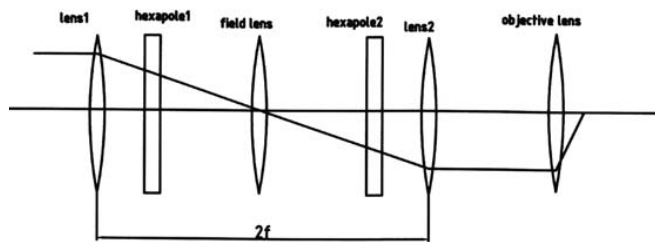


Fig. 1. Hexapole corrector system, design 1.

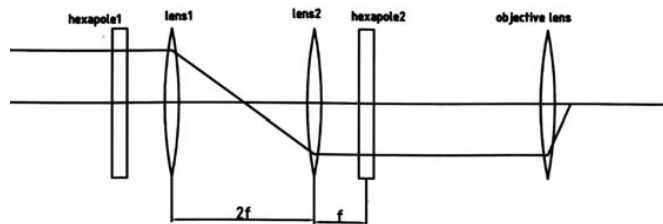


Fig. 2. Hexapole corrector system, design 2.

Design 1 consists of two hexapoles and three round lenses two of which terminate the system at the entrance and at the exit. The first round lens (entrance lens) forms a beam crossover in the middle between the two hexapoles. The last round lens (exit lens) is required to make the beam parallel again. Thus the distance between the first and last round lens centers is roughly equal to two focal lengths of the round lens ($2f$). The central round lens (field lens) is placed at the middle and its focal length is adjusted so that one hexapole is imaged on the other.

Design 2 consists of two hexapoles and two round lenses situated symmetrically between the hexapoles. The distance between the round lens centers is equal to two focal lengths ($2f$) and the distance between the hexapole centers is equal to four focal lengths of the round lens ($4f$). These two round lenses provide the same action as the three round lenses in the design 1: they create the beam crossover in the middle between hexapoles and they image one hexapole on the other.

Computer simulations of the hexapole correctors have been carried out for systems formed by a series of cylindrical electrodes aligned along the axis. Two of the cylinders are cut into six equal parts each to form hexapole elements. Alternating voltages $\pm V$ are applied to the neighboring segments of the hexapoles. Each round lens is formed by three cylinders. The outer cylinders are grounded and at the middle one an adjustable voltage is applied.

Both design 1 and design 2 have been simulated. Practical systems would of course use electrodes that do not have sharp edges but the present simulation is suitable for the present purpose of comparing the two designs of corrector.

In order to achieve reliable results on aberration correction it has been found necessary to use the highest available accuracies for the evaluation of the fields and for integrating the trajectories. It is also necessary to ensure that all the segments into which the electrodes are subdivided have an exact six-fold symmetry around the axis, which is achieved with one of the inherent options of the CPO3D program [11].

4. Adjustment of round lens voltages

The xz -section of design 1 generated by the CPO3D program is shown in Fig. 3. Note that the scales in x - and z directions are different. The diameter of the system is 10 mm and the total length is 120 mm. The three short cylinders on the left side form an entrance round lens and the similar three cylinders on the right form an exit lens, the third round lens (field lens) is placed in the middle of the system. Two identical hexapoles are placed symmetrically about the centre.

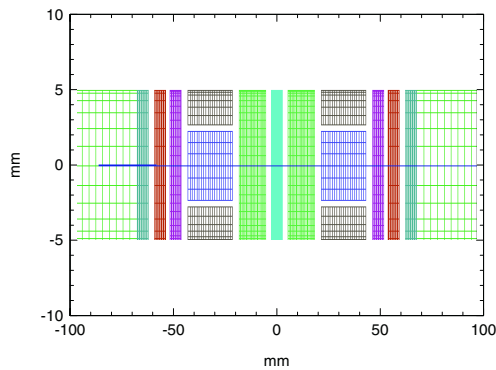


Fig. 3. The xz -section of the hexapole corrector (design 1) generated by the CPO3D program.

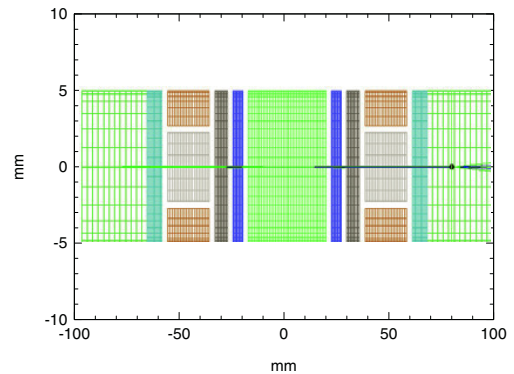


Fig. 4. The xz -view of design 2 of the hexapole corrector generated by the CPO3D program

The first step in adjusting the corrector voltages is to adjust those applied to the entrance and exit round lenses, which are equal to each other, so that the parallel beam which enters to the corrector forms a focus in the middle of the system and becomes parallel again at the exit. During this stage of the adjustment procedure all the other voltages are kept equal to zero.

The field lens voltage is the next to be adjusted. Since the magnitude of the field lens voltage does not depend on the hexapole voltages, the latter can be given arbitrary values at this stage. When the field lens is switched off the corrector introduces rather large fourth order aberration whose axial component has a three-fold symmetry [7]. The field lens voltage is therefore adjusted so that the initially round electron beam becomes round again after passing through the corrector. The magnitude of the required field lens voltage is found to be $V_f = 4.68$ in units of the voltage Φ , which determines the electron beam energy $-e\Phi$.

The value found for the field lens voltage might be too high from a practical point of view. Practically it would be easier to use a retarding voltage for the field lens, which would not result in much larger aberrations in comparison with an accelerating voltage because the electron trajectories cross the axis inside the field lens. It was found that a retarding voltage $V_f = -0.98$ applied to the field lens is equivalent to the accelerating voltage $V_f = 4.68$ and produces the same action.

The adjustment of voltages in design 2 is simpler than the analogous procedure in design 1 because only one round lens voltage is to be adjusted instead of two. We place the test plane at some distance downstream from the exit of the corrector and adjust the round lens voltages, which are equal to each other so that trajectory coordinates x_i and y_i in the test plane are exactly equal to the initial coordinates x_0 and y_0 of the same trajectory. This would ensure that the corrector forms an outgoing parallel beam from the incoming parallel beam and also forms an intermediate focus in the middle of the corrector. Due to the symmetrical geometry of the corrector this would automatically ensure that the hexapoles are identically imaged one to the other.

Fig. 4 shows the xz -section of design 2 generated by the CPO3D program. The basic dimensions of the system are the same as those of design 1.

5. Spherical aberration correction

The spherical aberration is corrected by adjusting the hexapole voltages. The procedure is the same for design 1 and 2. The objective lens is substituted in the simulation by an artificial thin lens with focal length $f = 2 \text{ mm}$ and spherical aberration coefficient $C_s = 1 \text{ mm}$. In practice the hexapole voltages are usually adjusted so that they minimize the electron probe size in the focal plane of the objective lens. In the case of computer simulation it is easier to observe not the focal plane but the xz - and yz - projections of the beam and to make the inner and outer rays of the beam fall at the same point along the z -axis which means that the spherical aberration is zero.

The xz -section of the beam is shown in Fig. 5 after the hexapole voltages have been adjusted so that they correct the third order spherical aberration of the total system of objective lens plus corrector. The beam crossover is now significantly reduced, which illustrates the effectiveness of the correction. Computations have shown that for an initial beam diameter of $100 \text{ } \mu\text{m}$, which corresponds to the aperture angle $\alpha = 0.025 \text{ rad}$, the spot size in the objective lens focal plane is reduced by a factor of 10 due to correction. As we do not consider the electron diffraction and chromatic aberration in this example (the beam energy spread is zero) the size of the probe obtained here for the corrected system is determined by higher order aberrations.

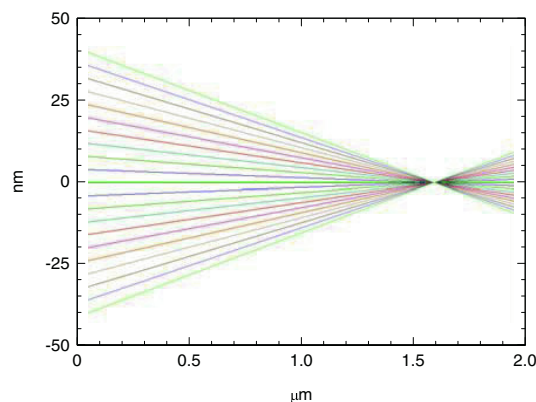


Fig. 5. The structure of the corrected beam near the focal plane of the objective lens

6. Automatic voltage adjustment

We have also used the ‘automatic focusing’ option of the CPO3D program to tune the correctors. In this option the simplex minimization routine is used to minimize the spot size by simultaneously varying all the relevant voltages. Essentially the same voltages are obtained, usually with a reduced spot size.

7. Chromatic and other aberrations

Since hexapoles do not have a first order focusing action (the primary action is of the second order) they do not affect axial chromatic aberration. The round lenses of the system do contribute chromatic aberration but since these lenses are much weaker than the objective lens their chromatic aberration is much smaller than that of the OL. This is confirmed by the computations, which show that the increase of the chromatic aberration caused by the corrector is usually very small and can be attributed not only to the effect of the round lenses but also to the computational inaccuracies.

The effects of using a non-parallel incident beam or an off-axis object have been studied and it has been found that these do not cause any deterioration in the performance.

One form of parasitic aberrations has also been studied for the LVSEM corrector, namely misalignment. It has been found that if a spot size of 1 nm is required the maximum permitted mis-alignment is $\sim 10\text{ nm}$ for design 1 and $\sim 50\text{ nm}$ for design 2.

The effects of voltage fluctuations have been studied for the LVSEM corrector. The maximum permitted voltage fluctuations for a deterioration in the spot size and position of 1 nm is $\sim 2\text{ mV}$ for design 1 and $\sim 1\text{ mV}$ for design 2.

8. Comparison of the two designs

Table 1 presents some computational results which illustrate the parameters of the corrected systems both for design 1 and design 2, when applied to the LVSEM.

Table 1

The hexapole corrector voltages and the total chromatic aberration coefficient C_c for the combination of the corrector plus objective lens of the LVSEM. The beam energy is 1 keV and all the voltages are in the units of kV . The focal length and spherical and chromatic aberration coefficients of the objective lens are 2.0 , 1.1 and 1.0 mm respectively.

Design	Round lens voltages	Field lens voltages	Hexapole voltages	Chromatic aberration coefficient C_c , mm
1	+1.483	+4.68	0.68	1.1
1	+1.483	-0.98	0.68	1.1
2	-0.872		0.25	2.1
2	+2.958		0.23	1.2

We see that the chromatic aberration increase is greater in design 2 in comparison with design 1 because the two round lenses of design 2 are stronger than the entrance and exit lenses of design 1 (if the length of the corrector is the same for both designs). The contribution of the field lens in design 1 to the chromatic aberration can be neglected (though the lens is strong) because the beam passes near the axis inside this lens. Evidently the retarding voltage applied to the round lens brings about greater chromatic aberration than the accelerating voltage, therefore applying an accelerating voltage can be recommended for the round lenses in design 2. In this case the total chromatic aberration is nearly the same in both designs. Note that the round lens voltage for design 2 (accelerating mode) is twice as large as the round lens voltages in design 1. Table 2 presents some illustrative computational results for the AnSEM.

Table 2 The hexapole corrector voltages and the total chromatic aberration coefficient C_c for the combination of the corrector plus objective lens of the AnSEM. The beam energy is 7 keV and all the voltages are in the units of kV . The focal length and spherical and chromatic aberration coefficients of the objective lens are 17 , 135 and 23 mm respectively.

Design	Round lens voltages	Field lens voltages	Hexapole voltages	Chromatic aberration coefficient C_c , mm
1	+3.76	-3.84	0.50	27
2	+4.3		0.04	30

Here round lenses of long focal length have been used (185 and 150 mm for designs 1 and 2 respectively) to reduce the chromatic aberrations. We see again that the increase C_c is larger for design 2.

Apart from the increase in C_c design 2 possesses some important advantages in comparison with design 1, for both the LVSEM and AnSEM:

(1) Design 2 is simpler, it contains fewer elements and needs a smaller number of independent voltages to be adjusted than design 1.

(2) The voltage adjustment in design 2 is much simpler than analogous procedure in design 1 and therefore can be performed more accurately.

(3) The hexapole voltages are smaller in design 2.

Computer simulations have also shown that the quality of the spherical aberration correction is better in design 2 which results in a smaller probe size. The system is less sensitive to the computational inaccuracies and therefore it would be less sensitive to mechanical defects.

9. Conclusions

The hexapole systems give a significant correction of the objective lens spherical aberration and can be recommended for incorporating into electron microscope columns in order to improve their performance.

The hexapole correcting systems are mechanically simpler than quadrupole-octupole correctors and what is more important the voltage adjustment in hexapole correctors is far less sophisticated than analogous procedure in quadrupole-octupole ones.

Due to the relative simplicity the hexapole correctors are less sensitive to mechanical defects and voltage instabilities.

The hexapole correctors do not allow chromatic aberration reduction and so therefore require that all possible measures be taken to reduce the electron beam energy spread.

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